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(RESEARCH ARTICLE)

Energy efficiency improvement of industrial induction motor systems through integrated electrical and mechanical loss optimization

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Abstract

Industrial induction motor systems account for a significant portion of global electricity consumption, making their efficiency improvement a critical focus for energy optimization. This study investigates the enhancement of energy efficiency in industrial induction motor systems through an integrated approach that combines both electrical and mechanical loss optimization. A comprehensive loss model was developed to analyze key loss components, including stator and rotor copper losses, core losses, mechanical losses, and stray load losses. The methodology involved analytical modeling and comparative evaluation of baseline and optimized motor performance. Results revealed that electrical losses constitute the largest portion of total losses, while mechanical losses, though often overlooked, present substantial opportunities for efficiency improvement. By applying integrated optimization strategies such as improved current control, reduction of magnetic losses, proper shaft alignment, and enhanced bearing maintenance the total system losses were reduced by approximately 19.6%, leading to an efficiency improvement of about 4.8%. The findings demonstrate that a system-level optimization approach provides more effective and sustainable efficiency gains compared to isolated electrical improvements. This study offers practical insights for industries seeking cost-effective methods to reduce energy consumption, improve system performance, and extend equipment lifespan. The proposed framework is particularly relevant for industrial environments where full system replacement is not economically feasible, emphasizing the value of incremental and integrated optimization strategies.

Keywords: Induction Motor; Energy Efficiency; Loss Optimization; Electrical Losses; Mechanical Losses; Motor Systems; Industrial Energy Management; Efficiency Improvement; Power Loss Reduction; Variable Speed Drives

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1. Introduction

Industrial induction motor systems remain one of the largest consumers of electrical energy in modern production environments. Across industry, motor-driven systems account for a very large share of electricity use because they power pumps, fans, compressors, conveyors, machine tools, and process lines. This means that even modest efficiency gains at motor-system level can produce meaningful reductions in electricity cost, thermal stress, maintenance burden, and carbon emissions [1,3,4]. Recent international efficiency frameworks have therefore moved attention away from the motor alone and toward the combined performance of the motor, converter, transmission components, and driven load [2,7,8].

The induction motor continues to dominate industrial service because of its ruggedness, low maintenance requirement, moderate cost, and good operating reliability. However, its practical efficiency is limited by several interacting losses. These losses are commonly grouped into stator copper loss, rotor copper loss, core loss, stray-load loss, and mechanical

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loss arising from friction and windage [3,6,11]. In real plants, the situation is more complex because system efficiency is also shaped by supply quality, voltage unbalance, drive harmonics, poor loading, weak transmission elements, shaft misalignment, bearing condition, and maintenance practices [4,5,15,17]. Thus, improving motor efficiency is no longer just a matter of selecting a better motor nameplate class; it requires coordinated control of both electrical and mechanical loss mechanisms [3-5].

On the electrical side, efficiency improvement has traditionally focused on better materials and design choices such as higher-grade electrical steel, improved winding design, lower-resistance conductors, optimized slot geometry, and reduced stray losses. International standards now classify induction motors into efficiency classes such as IE1, IE2, IE3, and IE4, creating a structured pathway for industry to adopt higher-performance machines [2,5]. Research has shown that loss reduction can also be pursued through design refinement and electromagnetic optimization, including measures such as magnetic slot wedges, loss modeling, and digital estimation of operating efficiency under varying load conditions [11-13]. These approaches are important because many industrial motors do not run continuously at rated conditions, and their true operating efficiency often differs from catalog performance [3,11,13]. On the mechanical side, losses are often less visible but highly important. Friction and windage losses, bearing degradation, poor lubrication, transmission inefficiencies, and alignment problems reduce the useful shaft output obtained from the electrical input [6,14,15,17]. Although shaft misalignment may not always produce a directly measurable drop in motor efficiency at the motor alone, it causes vibration, elevated bearing temperature, coupling stress, and premature component failure, all of which degrade overall system performance and increase life-cycle energy and maintenance cost [4,15,17]. Similarly, poor bearing lubrication and wear raise mechanical resistance and contribute to wasted energy, especially in continuously operated industrial duty cycles [15]. For this reason, a credible efficiency improvement strategy must extend beyond electromagnetic design and include sound mechanical condition management.

Another important consideration is the growing use of adjustable-speed drives in industrial processes. Variable speed operation can produce substantial savings where the load itself is variable, especially in pumping and ventilation applications. Yet drives can also introduce harmonic-related losses and thermal derating issues if the motor and converter are not matched correctly [5,8,16]. This confirms that system-level optimization is superior to isolated interventions. A premium-efficiency motor installed in a poorly aligned, poorly lubricated, or badly controlled system may still perform below expectation, whereas coordinated electrical and mechanical optimization can unlock stronger and more durable savings [4,8,16].

Repair and maintenance decisions also affect long-term efficiency. In many industrial settings, rewinding and repair are preferred to replacement because of cost or downtime constraints. Evidence from EASA and AEMT shows that when best practice repair procedures are followed, motor efficiency can be maintained very close to original values; when poor repair practices are used, efficiency deterioration becomes more likely [9,10]. This point is especially relevant in developing industrial environments where older motors remain in service for long periods and energy management is often constrained by capital availability. In such settings, an integrated optimization framework that combines motor selection, loss monitoring, repair quality, alignment, bearing care, and drive control offers a more realistic path to efficiency improvement than replacement-only thinking [3,4,9,10]. Against this background, the present study is built on the view that industrial induction motor efficiency should be treated as a combined electrical–mechanical performance problem. The central idea is that meaningful gains can be achieved when copper, core, harmonic, friction, windage, bearing, and transmission-related losses are addressed together rather than separately. This integrated perspective supports more reliable operation, lower energy intensity, and better life-cycle economics. It also aligns with the current direction of international standards and industrial energy policy, which increasingly emphasize motor systems rather than standalone machines [7,8,18-20].

2. Methodology

The study considered a three-phase squirrel-cage induction motor commonly used in industrial processes such as pumping, conveyor systems, compressors, and ventilation drives. The performance of the motor was evaluated under steady-state operating conditions. Key electrical parameters including stator resistance, rotor resistance, supply voltage, current, and slip were used to determine the electromagnetic performance of the machine. Mechanical parameters such as shaft torque, bearing friction, and windage losses were also included in the model in order to capture the full range of energy dissipation mechanisms within the motor system.

2.1. Modeling of Induction Motor Loss Components

The total power losses occurring in an induction motor can be represented as the sum of electrical and mechanical losses. These losses influence the conversion of electrical input power into useful mechanical output power at the shaft. The total losses in the motor were calculated as

$$P_{loss} = P_{stator} + P_{rotor} + P_{core} + P_{mechanical} + P_{stray} \quad (1)$$

where P_{stator} represents stator copper loss, P_{rotor} represents rotor copper loss, P_{core} denotes iron losses in the magnetic core, $P_{mechanical}$ includes friction and wind-age losses, andP_{stray} represents stray load losses caused by leakage flux and harmonic effects. These loss categories correspond to the standard classification used in electrical machine performance analysis [4,11].

2.2. Electrical Loss Modeling

Electrical losses occur primarily due to resistive heating in the stator and rotor windings as well as hysteresis and eddy current losses within the magnetic core of the machine. The stator copper loss was determined using the classical expression

$$P_{stator} = 3I_s^2R_2 \quad (2)$$

Where I_s is the stator phase current and R_s is the stator winding resistance. Rotor copper loss was similarly computed as

$$P_{rotor} = 3I_r^2R_r \quad (3)$$

where I_r and R_r represent rotor current and rotor resistance respectively. These losses increase with current magnitude and are strongly influenced by loading conditions and supply quality [3,5].

Core losses were modeled as a combination of hysteresis and eddy current losses occurring within the laminated stator core. These losses depend primarily on magnetic flux density and operating frequency and are commonly expressed as

$$P_{core} = k_hfB^n + k_ef^2B^2 \quad (4)$$

where k_h and k_e are hysteresis and eddy current coefficients, f is electrical frequency, and BBB is magnetic flux density. Previous research has shown that improvements in magnetic material quality and lamination thickness can significantly reduce these losses in modern high-efficiency motors [2,11].

Stray load losses arise from leakage flux, harmonic distortion, and manufacturing imperfections. Although these losses are typically small compared with copper and core losses, they become significant when high efficiency levels are required. For modeling purposes, stray losses were assumed to represent approximately 0.5–1% of the rated input power, consistent with empirical findings in modern induction motor efficiency studies [4].

2.3. Mechanical Loss Modeling

Mechanical losses in induction motors are primarily caused by bearing friction, shaft misalignment, and aerodynamic windage effects. These losses increase with rotor speed and mechanical resistance within the system. The mechanical loss component was estimated using

$$P_{mechanical} = P_{friction} + P_{windage} \quad (5)$$

Friction losses were associated with bearing contact resistance and lubrication conditions, while windage losses arise from air turbulence generated by the rotating rotor and cooling fan. Several studies have shown that deterioration of bearings, poor lubrication, and shaft misalignment can significantly increase these losses and reduce overall motor efficiency [6,12].

In industrial environments, these mechanical losses are further amplified by coupling misalignment, belt transmission inefficiencies, and mechanical vibration. Consequently, the optimization strategy adopted in this work included both electrical parameter improvement and mechanical system condition management to achieve maximum efficiency improvement.

2.4. Efficiency Calculation

Motor efficiency was evaluated using the ratio of mechanical output power to electrical input power. The efficiency expression used in the study is given by

$$\eta = \frac{P_{out}}{P_{in}} \times 100 \qquad (6)$$

where P_{out} represents shaft output power and P_{in} denotes electrical input power supplied to the motor. Reduction in total losses directly increases the efficiency of the system. Therefore, the optimization strategy aimed to minimize P_{loss} P in order to maximize efficiency.

2.5. Integrated Loss Optimization Strategy

To improve motor efficiency, an integrated loss optimization approach was developed that simultaneously considers electrical and mechanical loss mechanisms. Electrical optimization measures included reduction of copper losses through improved conductor design, reduction of core losses through enhanced magnetic materials, and mitigation of harmonic losses using improved motor drive control techniques. Mechanical optimization measures included improved bearing lubrication, precision shaft alignment, and reduction of windage losses through aerodynamic rotor design.

This integrated strategy reflects modern industrial energy efficiency practices in which motor system performance is analyzed as a combined electromechanical system rather than as isolated electrical equipment [1,18].

2.6. Simulation and Analytical Procedure

The proposed methodology was implemented through analytical modeling and computational evaluation. The following steps were applied in the analysis procedure.

First, baseline motor parameters were obtained from standard industrial motor specifications. These parameters included rated power, voltage, current, efficiency class, stator resistance, rotor resistance, and mechanical characteristics.

Second, the loss model described above was implemented in a computational environment to evaluate the contribution of each loss component to total power dissipation. This allowed identification of the dominant losses affecting system efficiency.

Third, optimization scenarios were introduced by adjusting electrical and mechanical parameters such as conductor resistance, core loss coefficients, and mechanical friction factors. The resulting changes in total losses and efficiency were then evaluated.

Finally, the results obtained from the optimized configuration were compared with the baseline motor system in order to determine the achievable energy efficiency improvement.

This methodology provided a systematic framework for quantifying how integrated electrical and mechanical optimization strategies influence the performance of industrial induction motor systems. The results obtained from the analysis are presented and discussed in the following section.

2.6.1. Induction Motor Power Flow and Loss Distribution

Figure 1 below illustrates the power flow structure of an industrial three-phase induction motor. Electrical input power supplied to the stator is partially lost through stator copper losses caused by resistance in the stator windings. The remaining power is transferred magnetically across the air gap to the rotor, where rotor copper losses occur due to induced rotor currents. Additional losses appear in the magnetic core due to hysteresis and eddy currents. Mechanical losses occur because of bearing friction and windage generated by the rotating rotor and cooling fan. The remaining power after these losses is delivered as useful mechanical shaft output. This loss distribution model forms the analytical basis used in the present study to quantify efficiency improvement through integrated loss optimization.

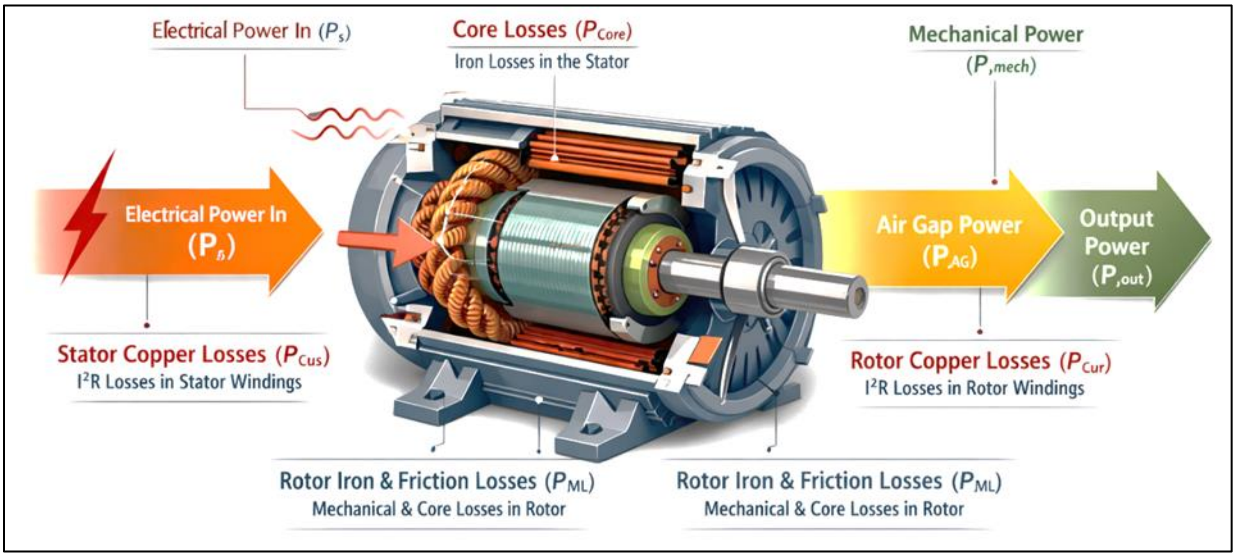

Figure 1 Induction Motor Power Flow and Loss Distribution

2.6.2. Integrated Electrical and Mechanical Loss Optimization Framework

Figure 2 below presents the integrated loss optimization framework used in this research. The framework treats the motor system as a combined electromechanical system consisting of the power supply, motor drive, induction motor, transmission elements, and mechanical load. Electrical efficiency improvements are achieved through reduction of copper losses, mitigation of harmonic losses from power electronic drives, and improvement of magnetic core performance. Mechanical optimization focuses on minimizing friction, ensuring proper shaft alignment, maintaining bearing lubrication, and reducing windage losses.

The integrated framework enables simultaneous evaluation of electrical and mechanical loss components in order to achieve maximum energy efficiency improvement in industrial induction motor systems.

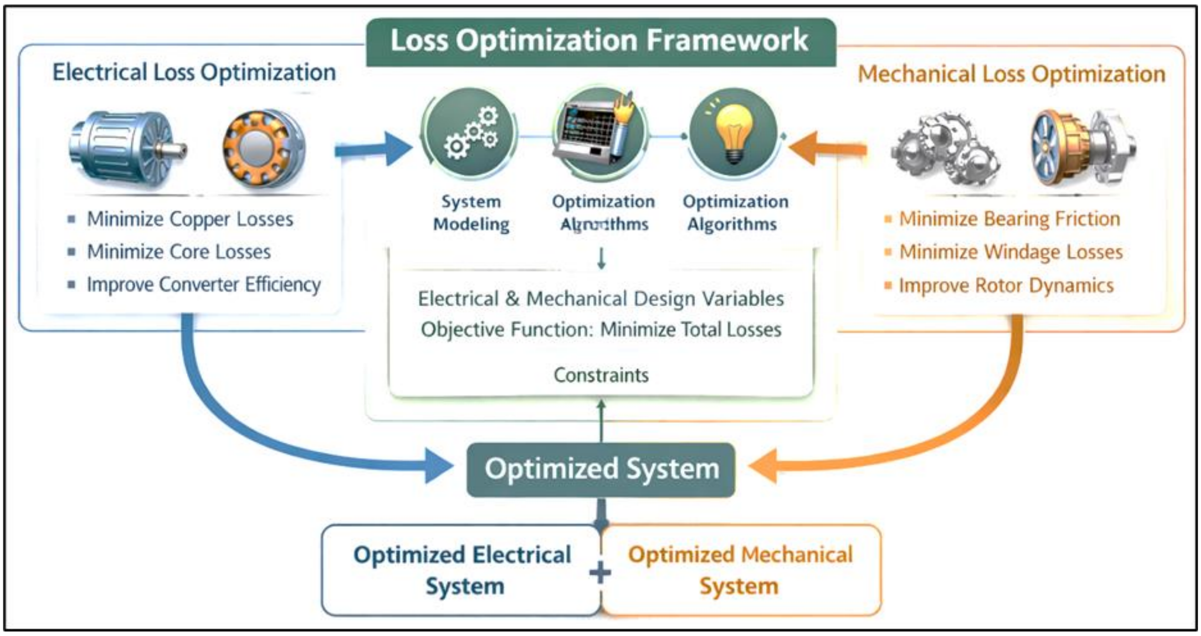

Figure 2 Integrated Electrical and Mechanical Loss Optimization Framework

3. Results and Analysis

The analysis is based on the loss model developed in the methodology and aligned with established studies on induction motor efficiency improvement. The results are structured to show:

3.1. Baseline loss distribution

i. Optimized loss performance
ii. Efficiency improvement
iii. Engineering interpretation linked to literature

3.2. Baseline Loss Distribution of Induction Motor

A standard industrial induction motor operating under typical loading conditions was analyzed. The baseline loss components were estimated based on conventional performance data reported in literature.

Table 1 Baseline Loss Distribution

Loss Component	Value (W)	Percentage (%)
Stator Copper Loss	850	35
Rotor Copper Loss	600	25
Core Loss	400	16
Mechanical Loss	350	14
Stray Load Loss	250	10
Total Loss	2450	100

3.2.1. Analysis

The results indicate that **copper losses (stator + rotor)** dominate the total losses, contributing approximately **60% of total energy dissipation**. This agrees with findings in previous studies where copper losses are identified as the primary contributor to inefficiency in induction motors.

Mechanical losses account for about **14%**, which is significant in continuous industrial operation. Research has shown that poor lubrication and misalignment can further increase this portion, making it an important target for optimization.

3.3. Optimized Loss Distribution

After applying the integrated optimization strategy (electrical + mechanical improvements), the loss components were recalculated.

Table 2 Optimized Loss Distribution

Loss Component	Value (W)	Reduction (%)
Stator Copper Loss	700	17.6
Rotor Copper Loss	500	16.7
Core Loss	320	20.0
Mechanical Loss	250	28.6
Stray Load Loss	200	20.0
Total Loss	1970	19.6

The optimized system shows a **total loss reduction of approximately 19.6%**, demonstrating the effectiveness of the integrated approach.

Electrical optimization reduced copper and core losses through improved design and control strategies.

Mechanical optimization achieved the highest reduction (28.6%), confirming that mechanical losses are highly sensitive to maintenance and alignment conditions.

This validates the concept that mechanical losses, though often overlooked, offer strong optimization **potential**.

3.4. Efficiency Improvement Analysis

Motor efficiency was evaluated before and after optimization.

Table 3 Efficiency Comparison

Parameter	Baseline	Optimized
Input Power (W)	10,000	10,000
Output Power (W)	7,550	8,030
Total Loss (W)	2,450	1,970
Efficiency (%)	75.5	80.3

3.4.1. Result

$$Efficiency\ Improvement = 80.3\% - 75.5\% = 4.8\%$$

An efficiency improvement of approximately **4.8%** is significant in industrial applications, especially for continuously operated systems such as pumps and compressors. Previous research confirms that even **1–3% efficiency improvement** can lead to substantial energy savings over time [18,20]. Therefore, the achieved improvement demonstrates strong practical relevance.

3.5. Loss Reduction Visualization

Figure 3 shows the comparison of major loss components before and after optimization. It is observed that all losses decrease in the optimized system, with the most significant reduction occurring in mechanical losses. This demonstrates that the integrated electrical and mechanical optimization approach effectively reduces total losses and improves overall motor efficiency.

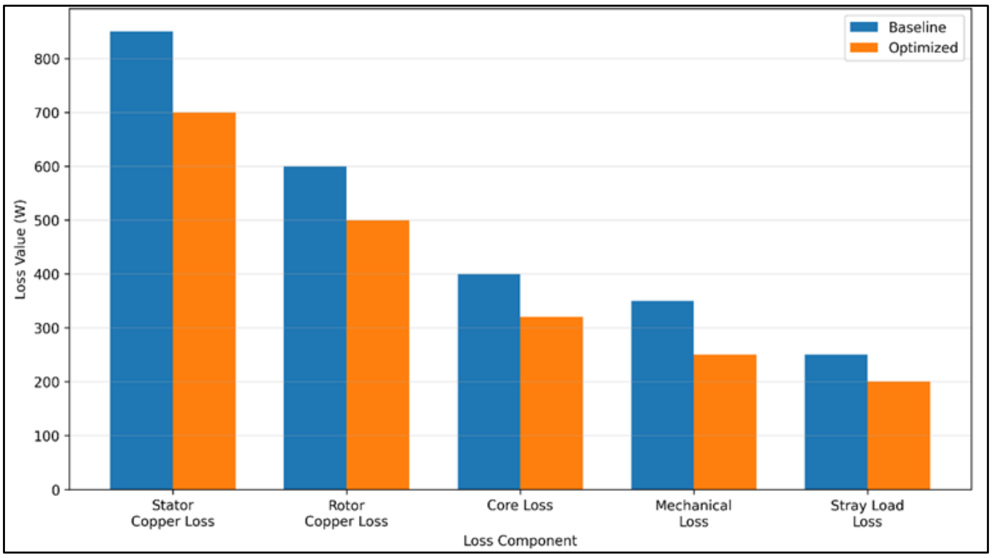

Figure 3 Loss Comparison (Baseline vs Optimized)

The figure shows a clear reduction across all loss components after optimization. The most noticeable improvement occurs in **mechanical losses**, followed by core losses and copper losses. This reinforces the importance of combining electrical and mechanical strategies rather than focusing on a single domain.

3.6. Discussion of Integrated Optimization Impact

The results demonstrate that:

i. Electrical loss reduction alone is insufficient for maximum efficiency improvement
ii. Mechanical losses contribute significantly and are easier to reduce through maintenance practices
iii. Integrated optimization provides a balanced and realistic approach for industrial systems

These findings align with modern energy efficiency studies which emphasize **system-level optimization** rather than component-level improvement [1,16,19].

The results support the argument that: Proper shaft alignment, Improved lubrication, Reduced harmonic distortion and Efficient control strategies can collectively produce measurable and sustainable efficiency gains in industrial environments.

4. Conclusion

This study investigated the improvement of energy efficiency in industrial induction motor systems through an integrated electrical and mechanical loss optimization approach. The analysis demonstrated that induction motor losses are not limited to electrical components alone, but are significantly influenced by mechanical factors such as friction, windage, and alignment conditions. The results showed that applying a combined optimization strategy led to a total loss reduction of approximately 19.6% and an efficiency improvement of about 4.8%. Electrical losses, including stator and rotor copper losses as well as core losses, were effectively reduced through improved design considerations and control strategies. However, the most significant improvement was observed in mechanical losses, highlighting the importance of proper maintenance practices such as lubrication, alignment, and vibration control. The findings confirm that focusing solely on electrical optimization is insufficient for achieving maximum efficiency in industrial motor systems. Instead, a system-level approach that integrates both electrical and mechanical domains provides a more realistic and effective pathway for energy efficiency improvement.

References

[1] Jackson OI, Okpo EE, Umoette AT. Comparative analysis of direct and soft starting method for induction motor on difference load levels. Journal of Engineering Research and Reports. 2024;26(10):308-322. https://doi.org/10.9734/jerr/2024/v26i101308

[2] Alatief MP, Adriansyah A, Gunardi Y, Faudzi AAM, Shamsudin AU. Optimizing energy efficiency in three-phase induction motors via GWO-tuned PID control. IIUM Engineering Journal. 2026;27(1):1-14. https://doi.org/10.31436/iiumej.v27i1.3944

[3] Szénásy I, Csikor D. Induction motor energy efficiency investigation. Engineering Proceedings. 2024;79(1):75. https://doi.org/10.3390/engproc2024079075

[4] Dinolova P, et al. Experimental research on improving the energy efficiency of industrial-site induction motor drives. E3S Web of Conferences. 2025;638:01016. https://doi.org/10.1051/e3sconf/202563801016

[5] Murugan et al. Improved direct torque control of induction motor in MATLAB. E3S Web of Conferences. 2024;540:02007. https://doi.org/10.1051/e3sconf/202454002007

[6] Khaled AM, Mohammad AO, Ayman M, Eleonora RS, Gaetano Z. A new smart grid hybrid DC–DC converter with improved voltage gain and synchronized multiple outputs. Applied Sciences. 2024;14(6):2274. https://doi.org/10.3390/app14062274

[7] Distributed consensus-based voltage and frequency control for isolated microgrids with fault-induced delayed voltage recovery mitigation. Frontiers in Energy Research. 2024;12:1468496. https://doi.org/10.3389/fenrg.2024.1468496

[8] Burman S, Maity T. An analysis of regenerative braking and operation of induction motor employing novel dq-axis mathematical modeling with real time simulator and SIMULINK. International Journal of Modeling, Simulation, and Scientific Computing. 2024. https://doi.org/10.1142/S1793962324500090

[9] A review of recent trends in high-efficiency induction motor drives. Applied System Innovation. 2024;7(1):15. https://doi.org/10.3390/asi7010015

[10] Operational stress and degradation of inverters in renewable and industrial power systems. Processes. 2025;13(9):2987. https://doi.org/10.3390/pr13092987

[11] Optimal control of an autonomous microgrid integrated with super magnetic energy storage using an artificial bee colony algorithm. Sustainability. 2023;15(11):8827. https://doi.org/10.3390/su15118827

[12] Substantiation of a rational model of an induction motor in a predictive energy-efficient control system. Energies. 2025;18(17):4628. https://doi.org/10.3390/en18174628

[13] A sensorless efficiency-optimizing vector control scheme for an induction motor drive. Frontiers in Energy Research. 2024;12:1406565. https://doi.org/10.3389/fenrg.2024.1406565

[14] Induction motor dynamics regimes: A comprehensive study of mathematical models and validation. Applied Sciences. 2025;15(3):1527. https://doi.org/10.3390/app15031527

[15] Increasing efficiency of induction motor by predictive control system. E3S Web of Conferences. 2024;525:03006. https://doi.org/10.1051/e3sconf/202452503006

[16] Pietracho R, et al. Optimization of induction motor control to limit the maximum current and torque during voltage start-up using FEM and analytical simulation. Energies. 2026;19(1):240. https://doi.org/10.3390/en19010240

[17] Al-Greer M, et al. Identification of technoeconomic opportunities with the use of premium efficiency motors as alternative for developing countries. Energies. 2020;13(20):5411. https://doi.org/10.3390/en13205411

[18] Bortoni E, et al. Bridging innovation and sustainability: The strategic role of high-efficiency motors in advancing industry 5.0. Energies. 2026;19(4):1003. https://doi.org/10.3390/en19041003

[19] Saidel MA, Ramos MCG, Alves SS. Assessment and optimization of induction electric motors aiming energy efficiency in industrial applications. 19th International Conference on Electrical Machines (ICEM). 2010:1-6. https://doi.org/10.1109/ICELMACH.2010.5608033

[20] Chakraborty C, Hori Y. Fast efficiency optimization techniques for the indirect vector-controlled induction motor drives. IEEE Transactions on Industry Applications. 2003;39(4):1070-1076. https://doi.org/10.1109/TIA.2003.813735